Transverse Spin Results from PHENIX at RHIC

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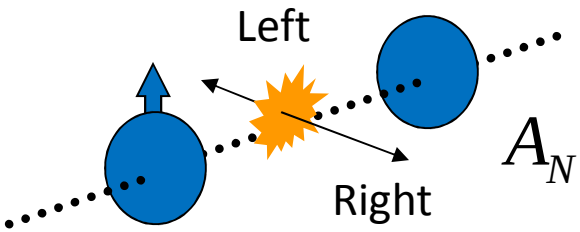
New Mexico State University

- Introduction
- PHENIX measurements and results
- Opportunities with new detectors

Single Transverse Spin Asymmetries



$$A_N = \frac{1}{P}\frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

Theory Expectation (twist-2):

Small asymmetries at high energies
(Kane, Pumplin, Repko, PRL 41, 1689–1692 (1978))

$$A_N \propto \frac{m_q}{\sqrt{s}}$$

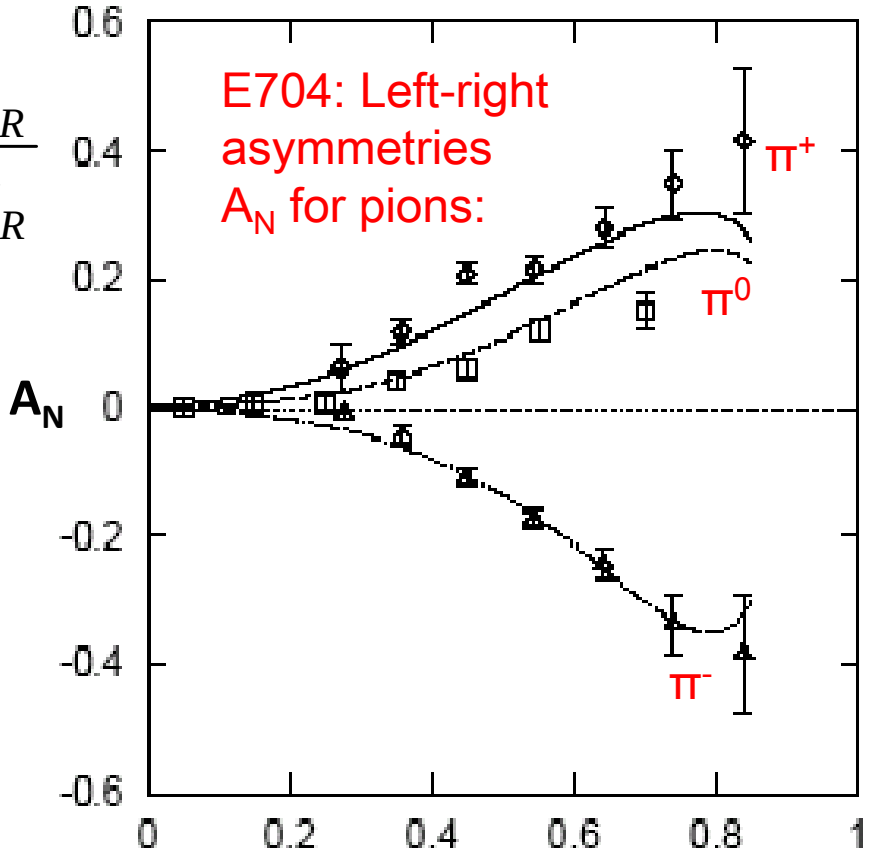
A_N ~O(0.1%) Theory

Experiment:

(E704, Fermi National Laboratory, 1991)

$$pp^{\uparrow} \rightarrow \pi + X$$
$$\sqrt{s} = 20\,\mathrm{GeV}$$

A_N ~O(10%) Measured

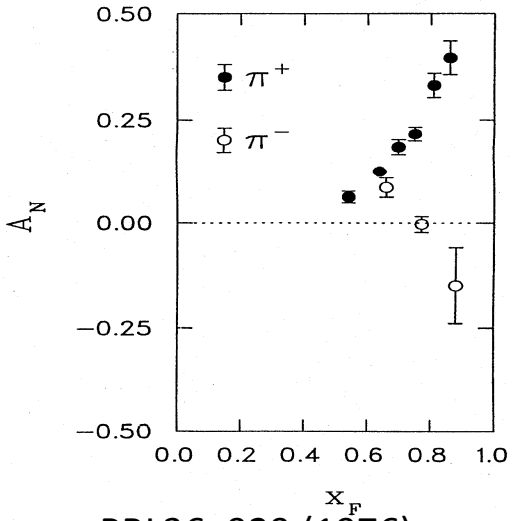


$$x_F = \frac{2p_L}{\sqrt{s}}$$

How can we understand them?

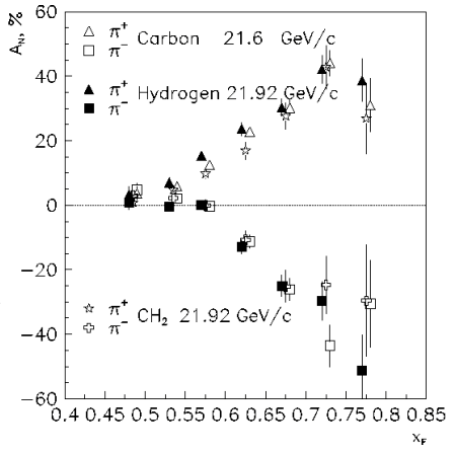
Large Transverse Single Spin Asymmetry (SSA) in forward hadron production persists up to RHIC energy.

ZGS $\sqrt{s} = 5\ GeV$



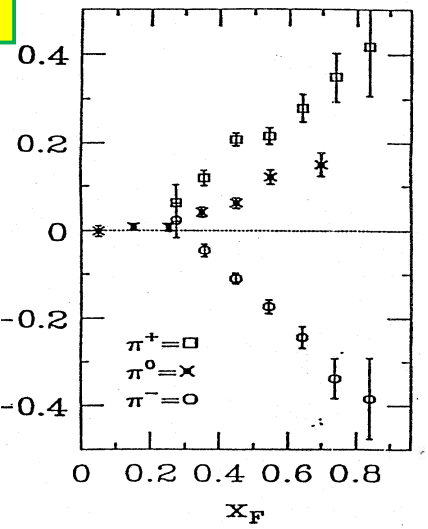
PRL36, 929 (1976)

AGS $\sqrt{s} = 7\ GeV$



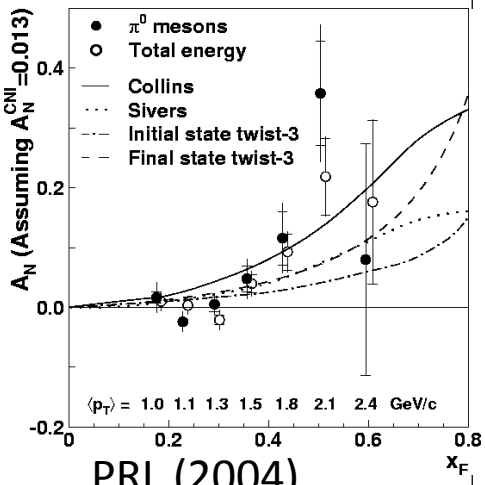
PRD65, 092008 (2002)

FNAL $\sqrt{s} = 20\ GeV$

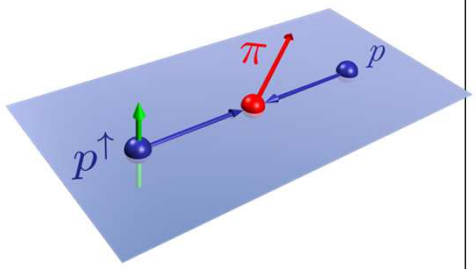


PLB261, 201 (1991)
PLB264, 462 (1991)

RHIC $\sqrt{s} = 200\ GeV$

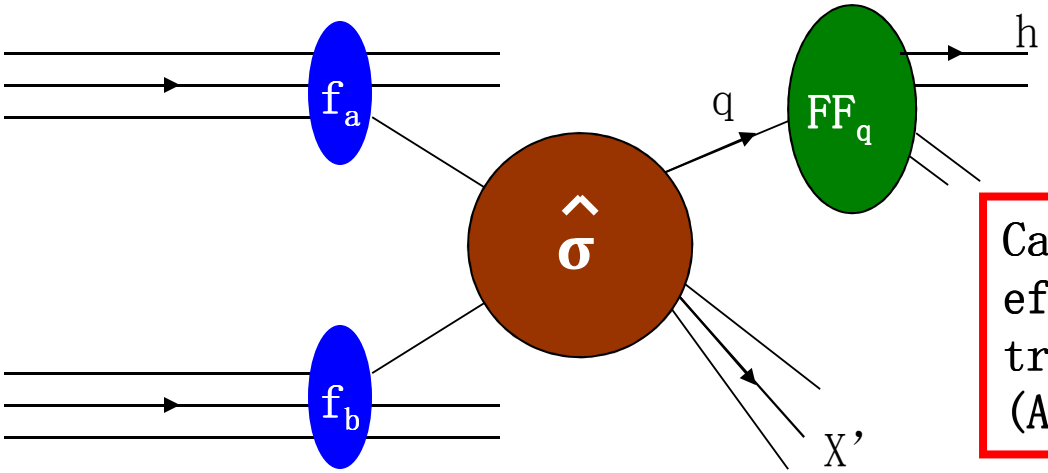


PRL (2004)



Non-Perturbative cross section → Perturbative cross section

Possible Origin of Large SSAs



Can initial and/or final state effects generate large transverse spin asymmetries? (A_N ~10^{-1})

Proton Structure **pQCD**

$$\frac{d^3\sigma^{\uparrow}\left(pp^{\uparrow}\rightarrow\pi^{+}X\right)}{dx_1dx_2dz}\propto q_i^{\uparrow}(x_1,k_{q,T})\cdot G(x_2)\times\frac{d^3\hat{\sigma}^{\uparrow}(q_iq_j\rightarrow q_kq_l)}{dx_1dx_2}\times FF_{q_{k,l}}(z,p_{h,T})$$

small spin dependence

fragmentation function

Mechanisms in QCD

TMD mechanism: GPM includes intrinsic transverse momentum

Possible Expansion:

$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \propto f_{1T}^{\perp} \otimes D_1 + \delta q \otimes H_1^{\perp} + \ldots$$

Sivers Function (angular momentum) → Sivers Effect

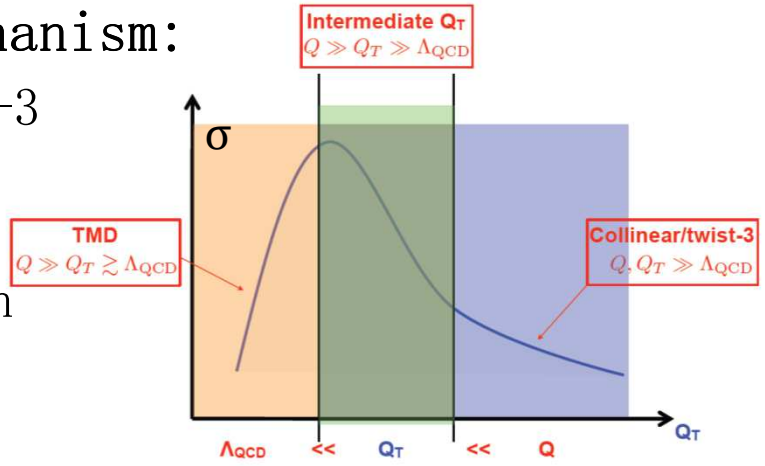
Transversity (structure)

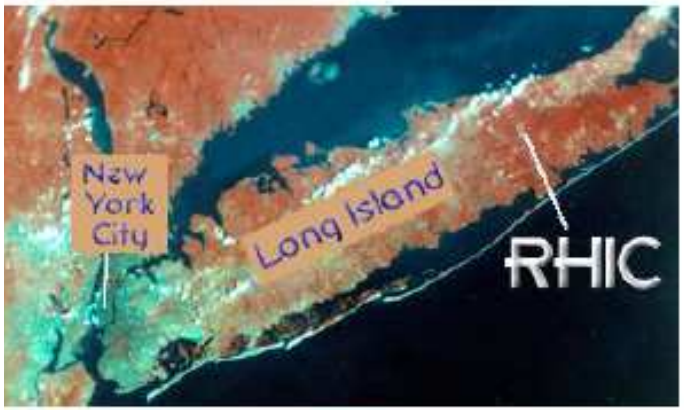
Collins Function (Fragmentation) → Collins Effect

Twist-3 Collinear factorization mechanism:

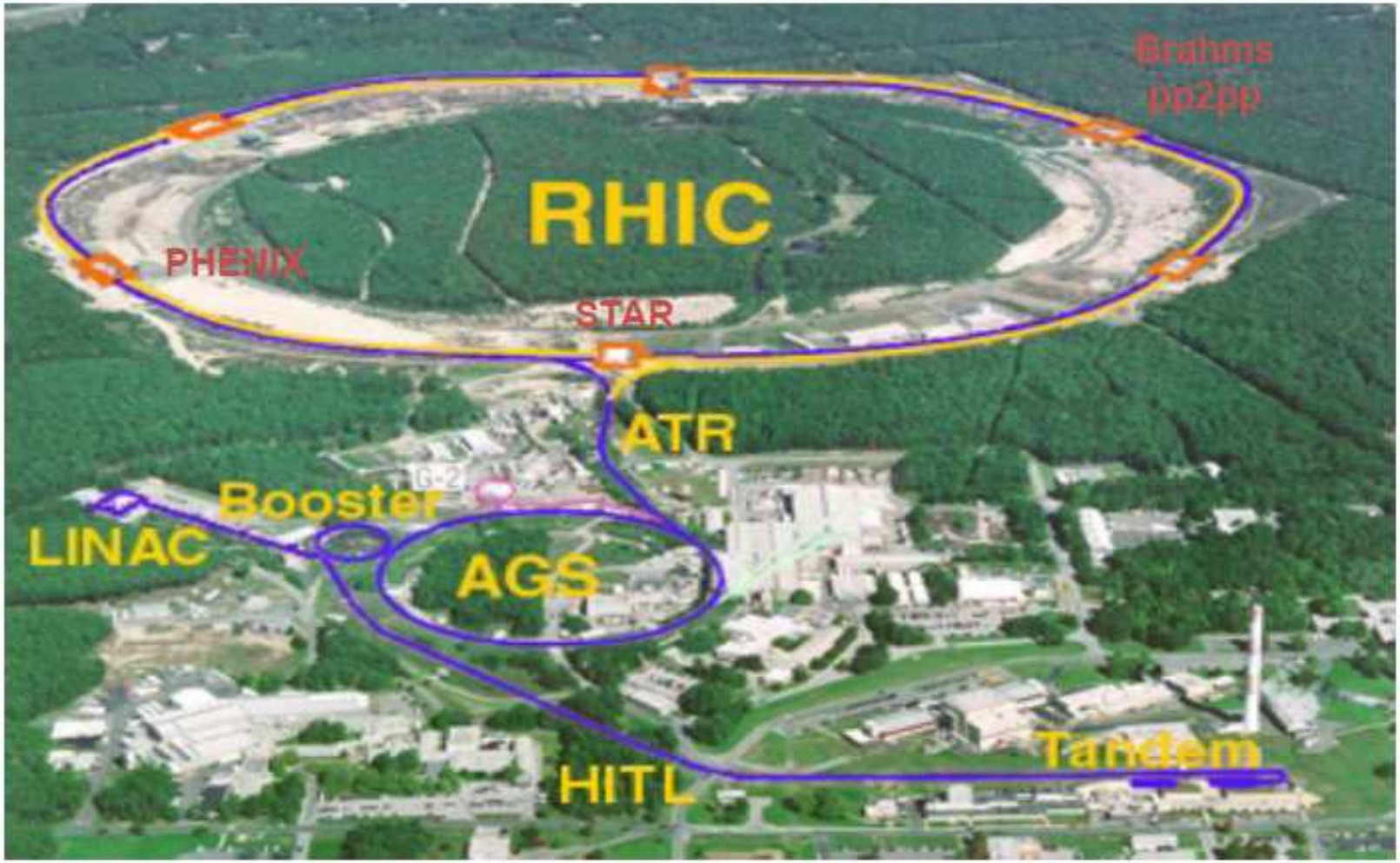
At high transverse momenta : two twist-3 correlation functions

1. Quark-gluon correlation function $T_{q,f}$
2. Two independent trigluon correlation functions $T_G^{(f)}, T_G^{(d)}$

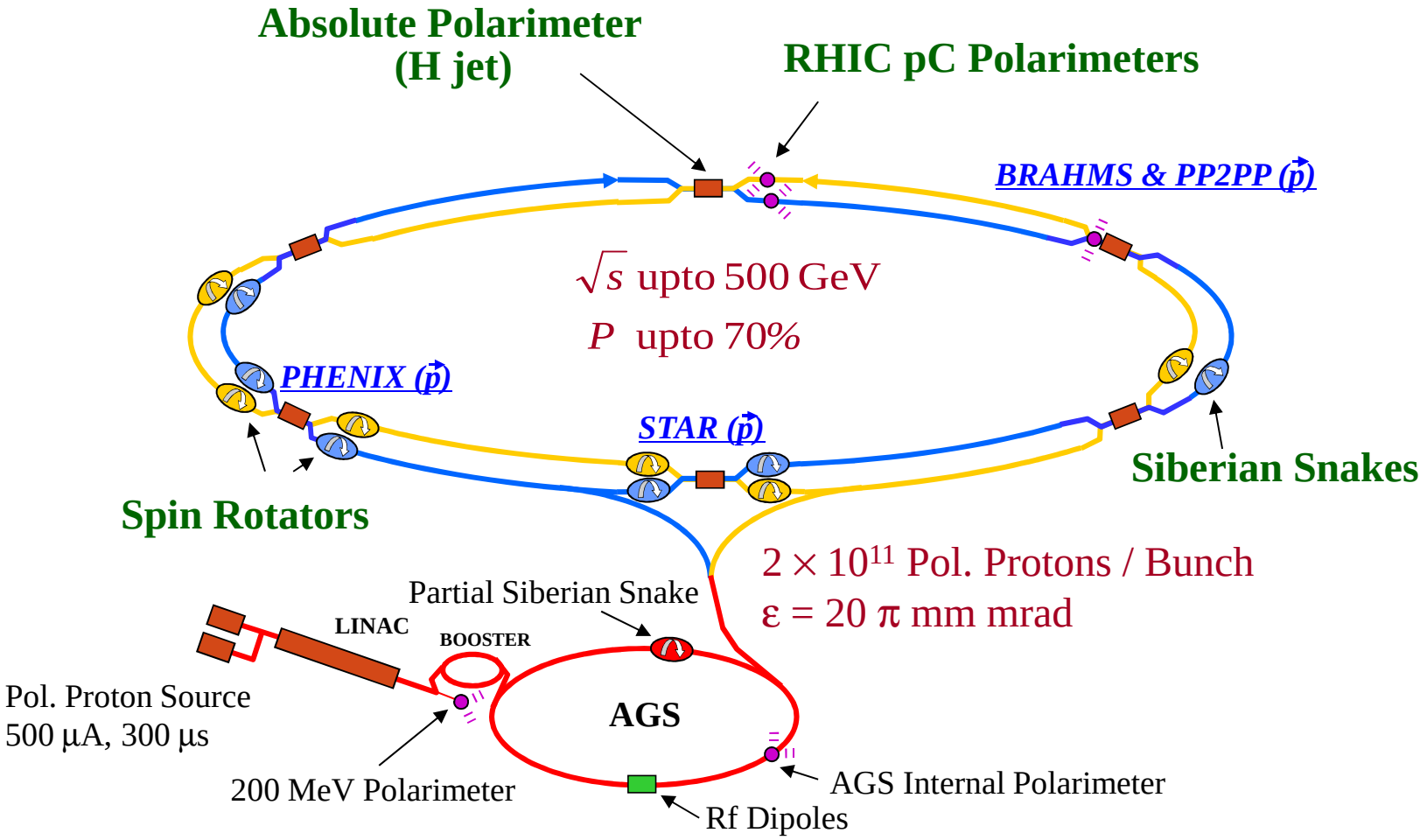




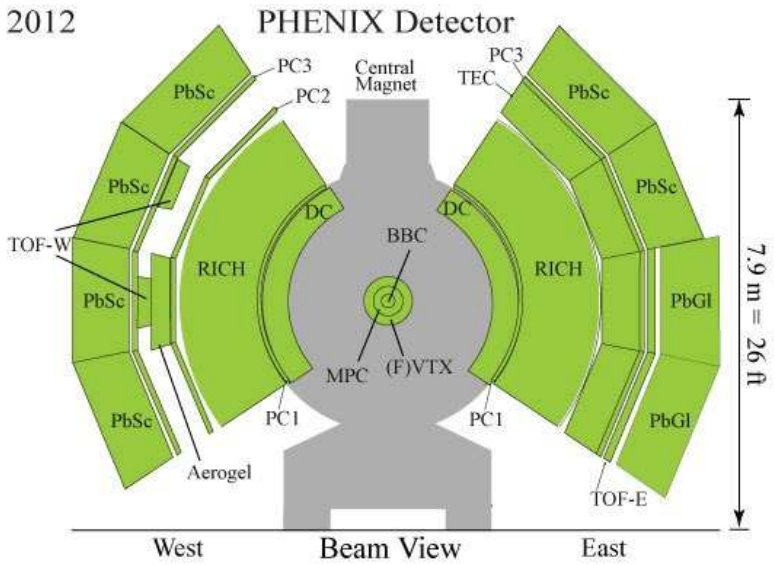
The Relativistic Heavy Ion Collider accelerator complex at Brookhaven National Laboratory

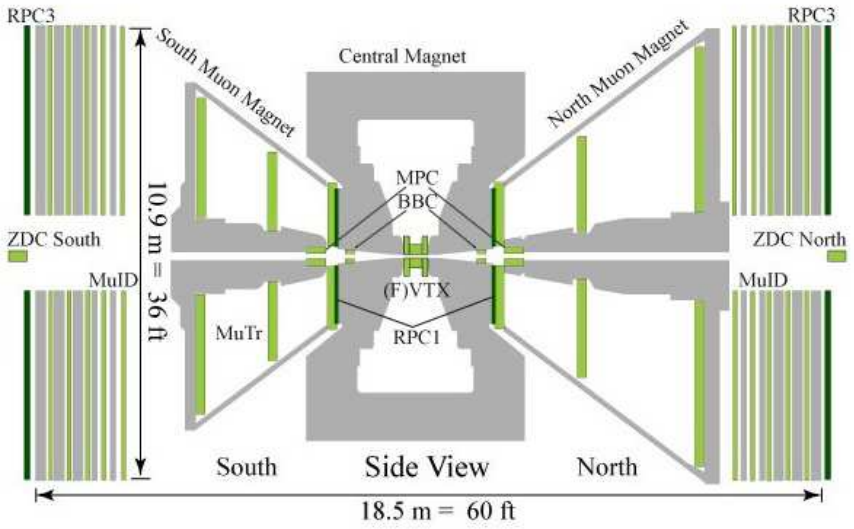


RHIC as Polarized Proton Collider



PHENIX Detectors





- **Central Arm** $|\eta|<0.35$, $\Delta\varphi=2 \times \pi/2$
  - Drift Chamber (DC)
  - PbGl and PbSc (EMCal)
  - Ring Imaging Cherenkov Detector(RICH)
  - Pad Chambers (PC)
  - Time Expansion Chamber (TEC)
  - Silicon Vertex Detector (VTX)
- **Muon Arms** $1.2<|\eta|<2.4$, $\Delta\varphi=2\pi$
  - Muon tracker (MuTr)
  - Muon Identifier (MuID)
  - RPC (Trig)
  - Forward VTX (FVTX)
- **Muon Piston Cal. (MPC)** $3.1<|\eta|< 3.9$
  - **Photons**
  - **MPX-EX upgrade (2015)**
- **Global Detectors (Lumi, Trigger, local Pol.)**
  - **BBC**
  - **ZDC (neutron)**

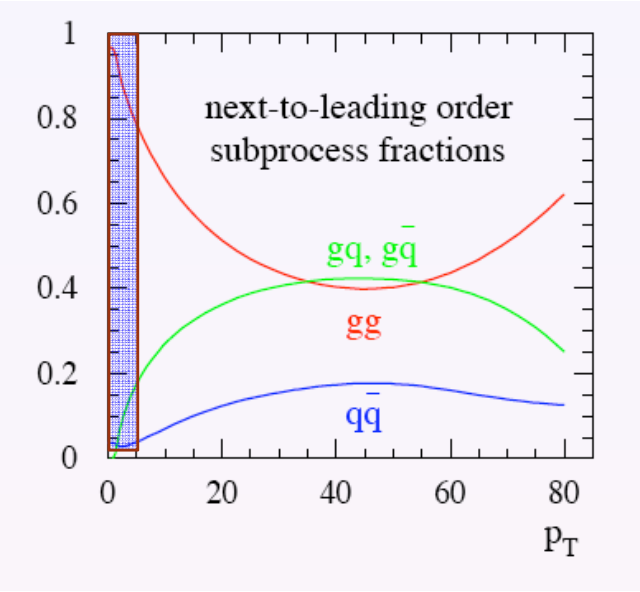
Integrated Luminosity and Polarization

Year of RHIC Run	Energy [GeV]	Polarization [%]	Recorded L [pb^{-1}]	FOM (P^2L) [nb^{-1}]
2002	200	15	0.15	3.4
2005	200	47	0.16	35
2006	62.4	48	0.02	4.6
2006	**200**	**50**	**2.7**	**700**
2008	**200**	**45**	**5.2**	**1100**
2012	**200**	**60**	**9.2**	**3300**

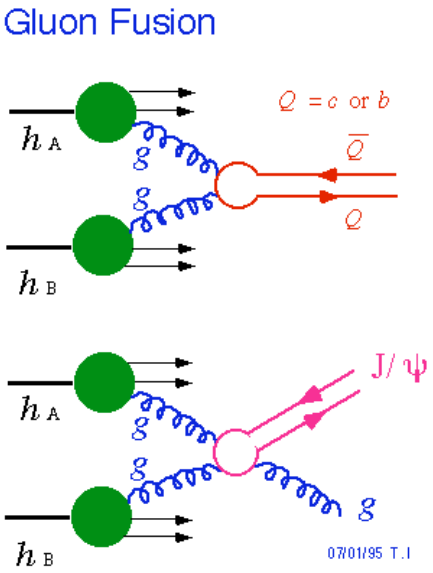
PHENIX Measurements and Results

The Gluon Sivers measurement

- Can we separate the Sivers and Collins effects?



Heavy flavor production dominated by gluon-gluon fusion at RHIC energy



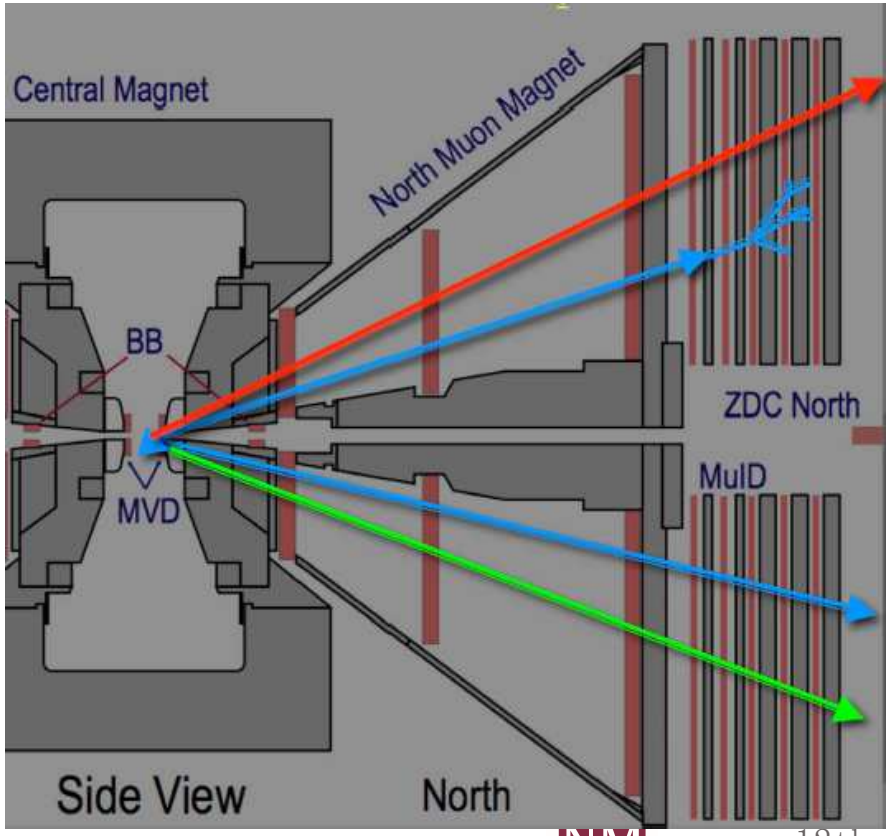
- Eliminate the Collin's effects since gluon has no transversity
- Sensitive to gluon Sivers function

Measurement of Heavy flavor decay muon

Muon Spectrometer:

- 1.2<|η|<2.4
- Azimuthal: ΔΦ=2π

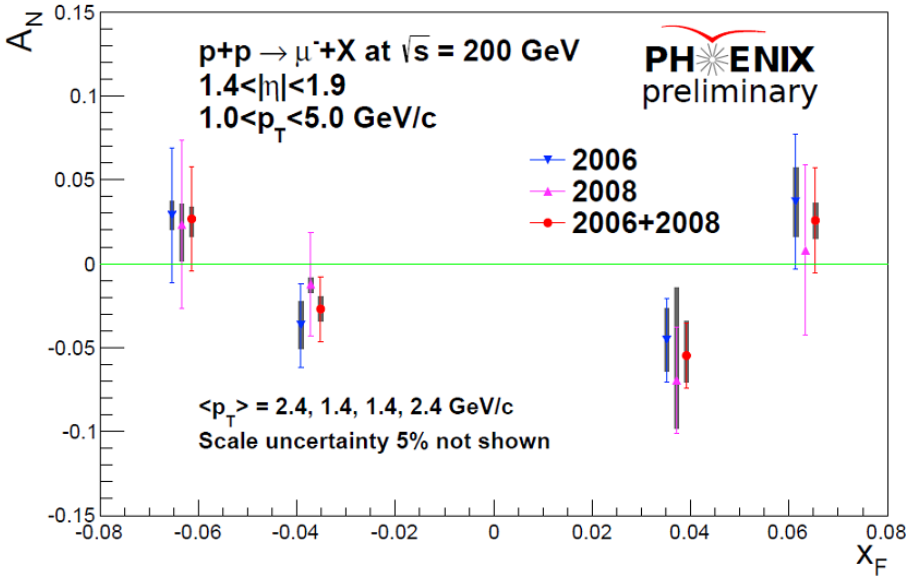
$$A_N^{Phys} = \frac{A_N^{Incl} - r \cdot A_N^{BG}}{1 - r} \qquad r = \frac{N^{BG}}{N^{Incl}}$$



Inclusive Muons

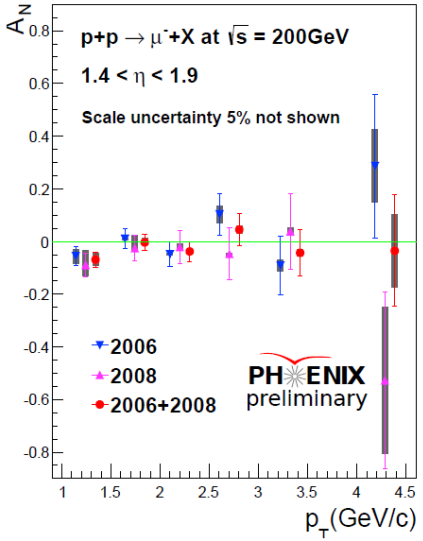
- Heavy Flavor decay muons
- Stopped hadrons → Distinguished background
- Non-distinguished background
- Punch-through hadrons
- Hadron decay muons

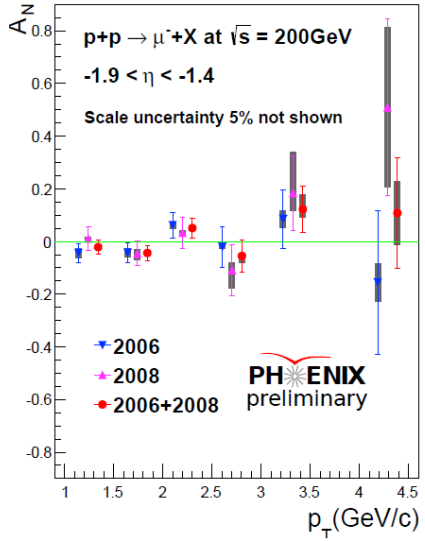
A_N of heavy flavor decay muon



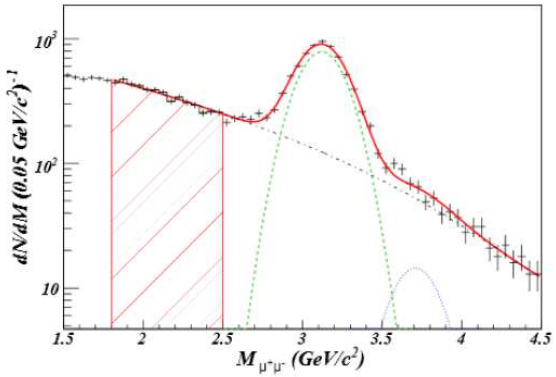
- Currently Measured A_N are consistent with zero.
- A larger 2012 data sample will increase sensitivity. The analysis is on progress.

- New installed FVTX detector will provide better rejection on hadron background in future

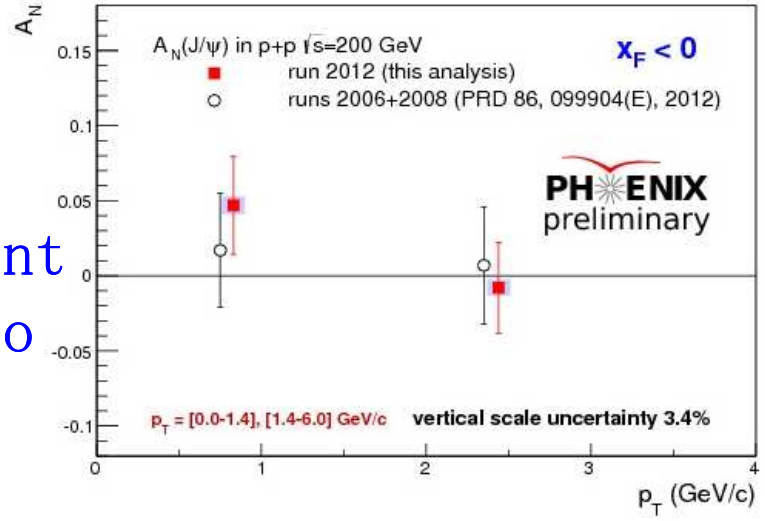


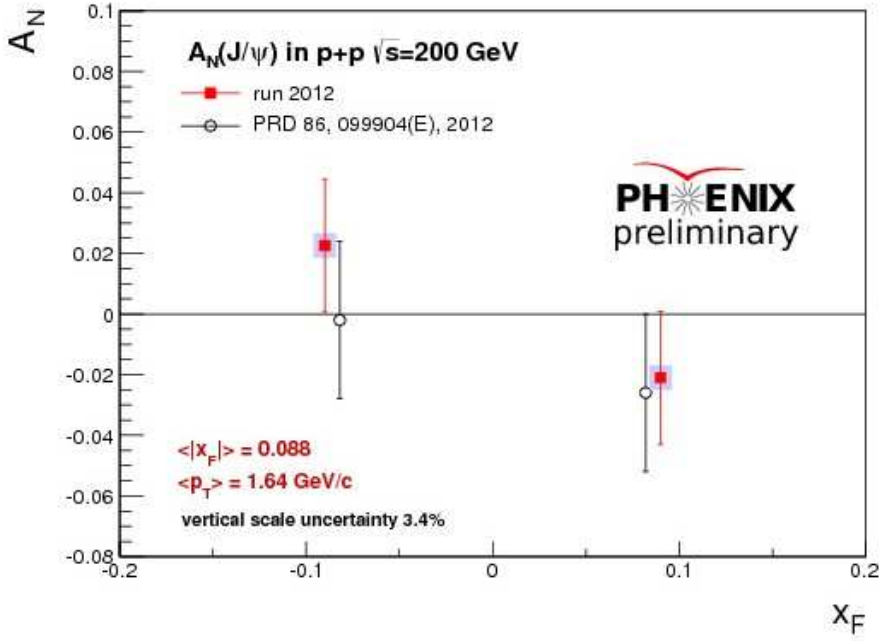


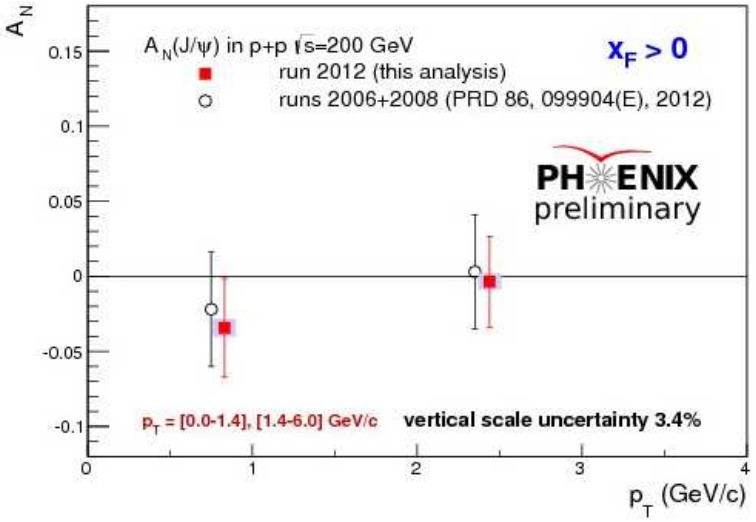
A_N of J/ψ



The results are consistent with zero too

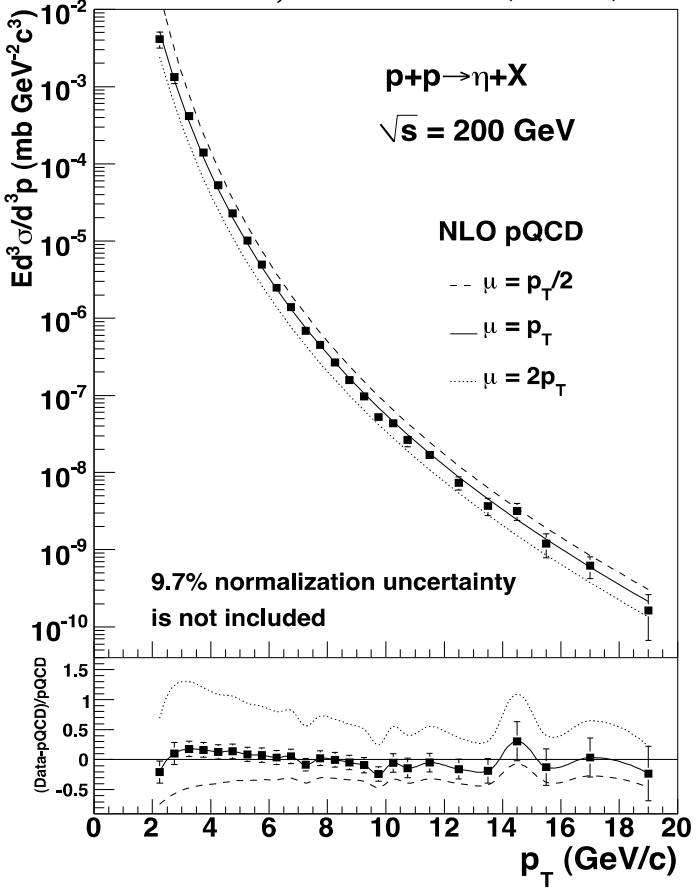


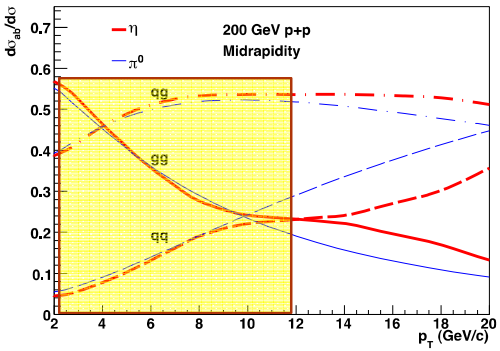


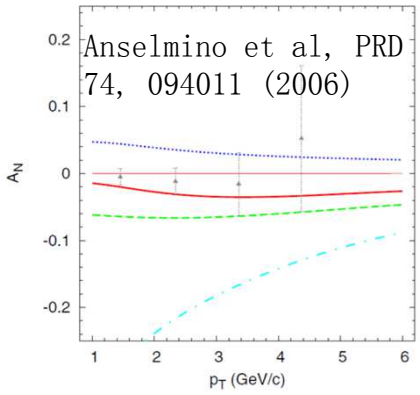


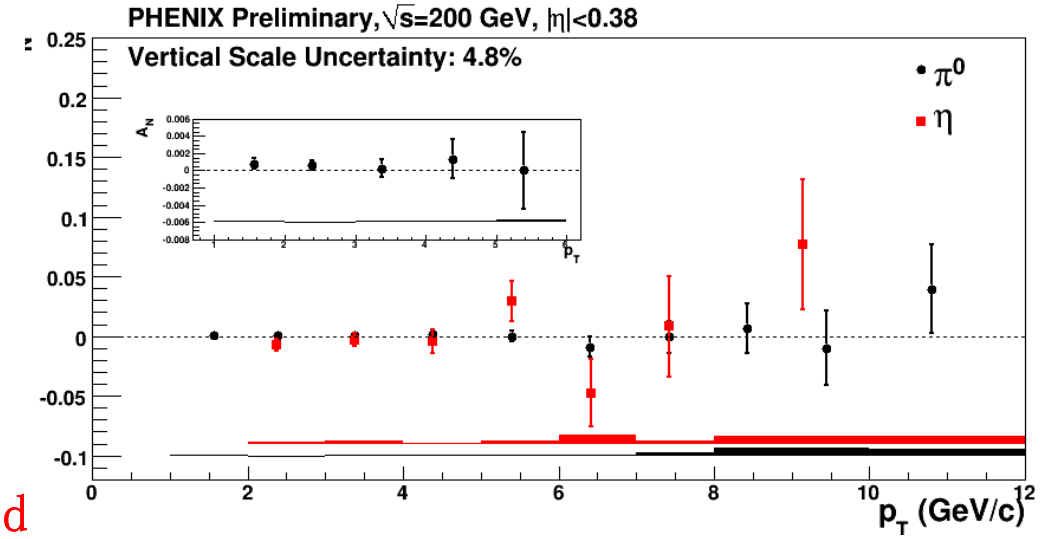
A_N of Mid-rapidity π^0 and η

PRD 83, 032001 (2011)





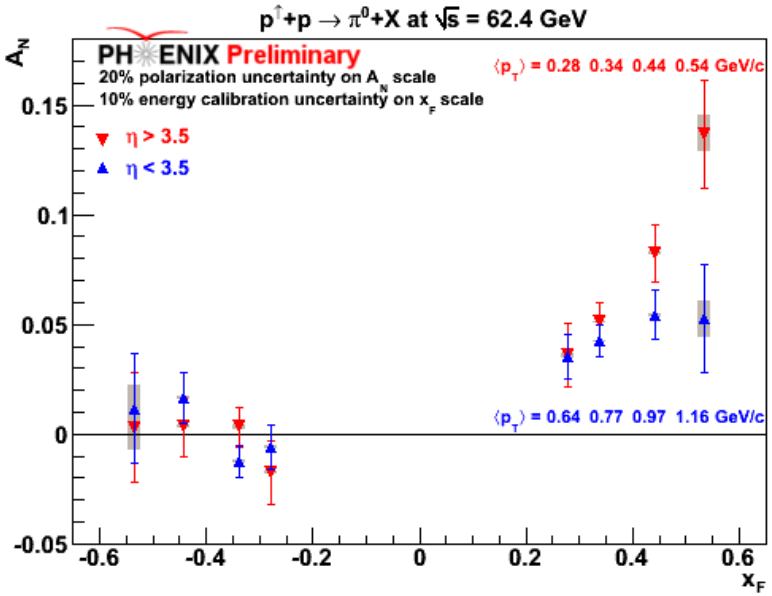


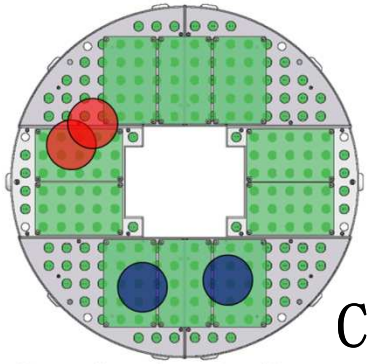


Cross sections: pQCD in good agreement with RHIC data

A_N: consistent with zero.

Forward A_N for MPC Clusters



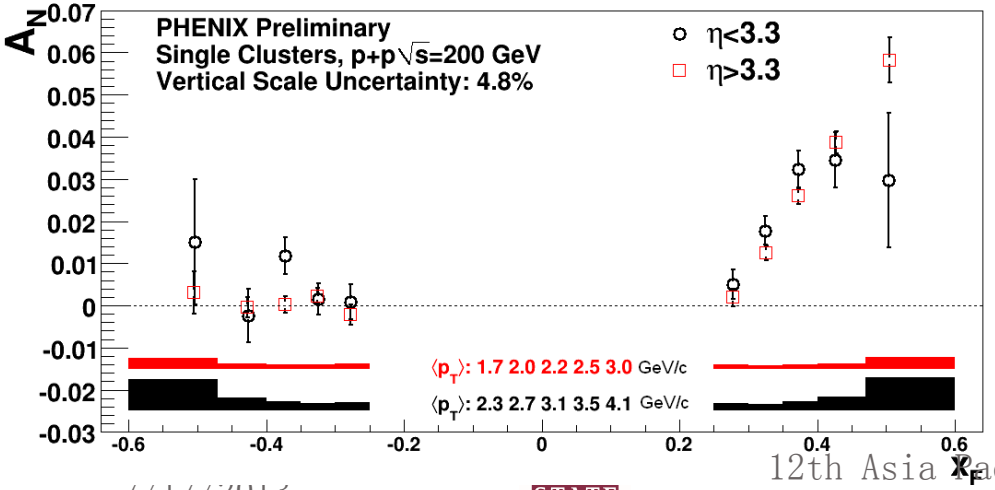


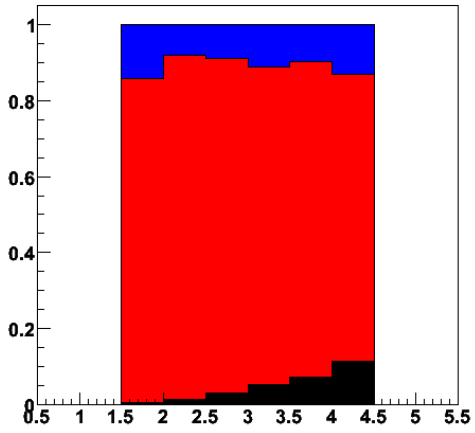
Decay photon impact positions for low and high energy π^0's

Measurements from MPC $3.1<|\eta|<3.9$

Cluster contribution

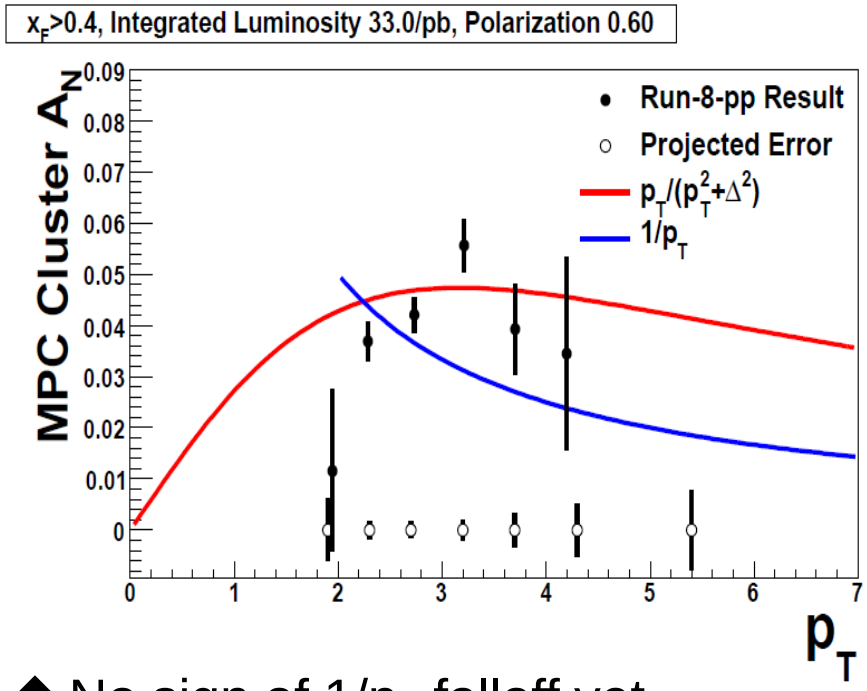
- Decay photon
- π^0
- Direct photon



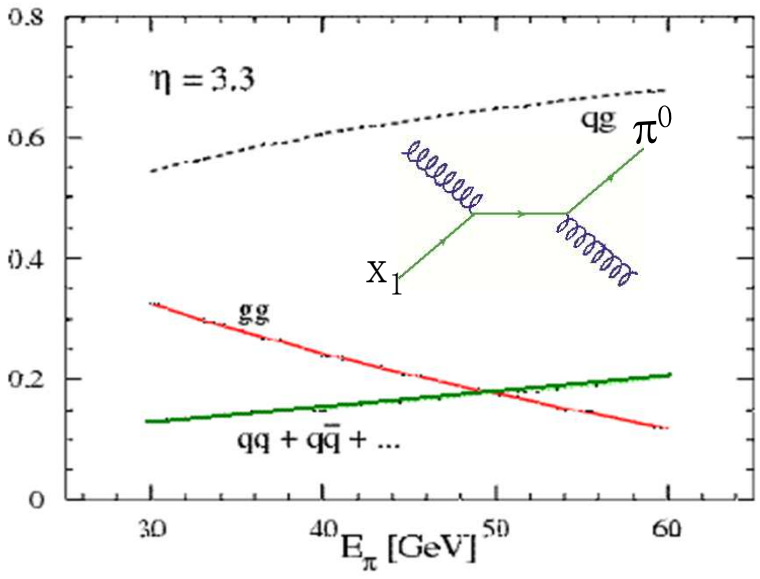


Forward A_N Challenge: p_T Dependence

Valence Quarks' Sivers or Collins effects?



Sub-process fractions p+p 200GeV



- No sign of $1/p_T$ falloff yet.
  - Collins?
  - Twist-3 p_T dependent not trivial
- Much improved with MPC-EX (2015+)

$$A_N \sim \frac{1}{Q} \quad @twist-3$$ Y. Koike, 2012

$$A_N \sim O\left(\frac{M_N P_T S}{UT}\right) + O\left(\frac{M_N P_T}{-U}\right)$$

Interference Fragmentation

Interference Fragmentation Function (H_1):

Fragmentation of a transversely polarized quark q into two spin-less hadron h1, h2 carries an azimuthal dependence

$$d\sigma_{UT} = 2|P_{C\perp}||S_{BT}|\sin(\varphi_S - \varphi_R)\sum_{a,b,c,d}\int \frac{dx_a dx_b}{16\pi z_c} f_1^a(x_a) h_1^b(x_b) \frac{d\Delta\hat{\sigma}_{ab^\uparrow\to c^\uparrow d}}{d\hat{t}} H_{1,ot}^{\sphericalangle c}(\bar{z}_c, M_C^2)$$

$$A_{UT} = \frac{\sigma_{UT}}{\sigma_{UU}} \longrightarrow d\sigma_{UU} = 2|P_{C\perp}|\sum_{a,b,c,d}\int \frac{dx_a dx_b}{4\pi^2 z_c} f_1^a(x_a) f_z^b(x_b) \frac{d\hat{\sigma}_{ab\to cd}}{d\hat{t}} D_{1,00}(\bar{z}_c, M_C^2)$$

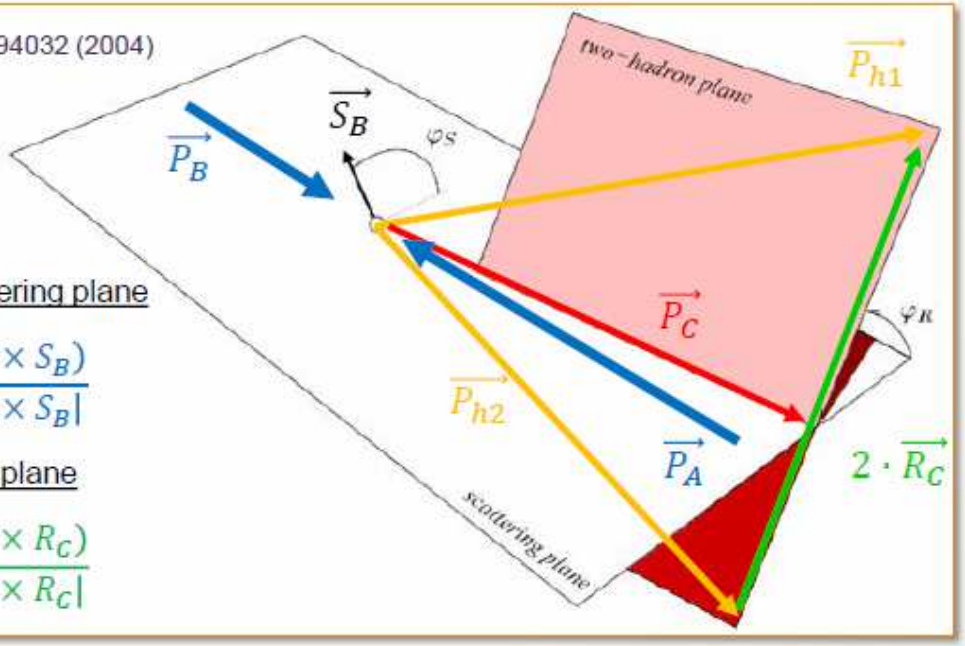
Transversity

$\otimes$

IFF

Collins!

A. Bacchetta, M. Radici, PRD 70, 094032 (2004)



from polarization vector to scattering plane

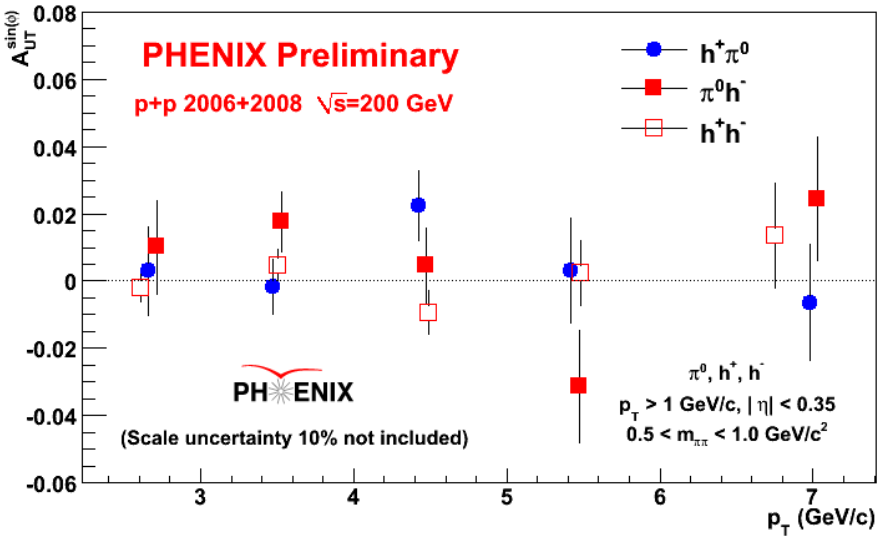
$$\cos\varphi_S = \frac{(P_B \times P_C)}{|P_B \times P_C|}\cdot\frac{(P_B \times S_B)}{|P_B \times S_B|}$$

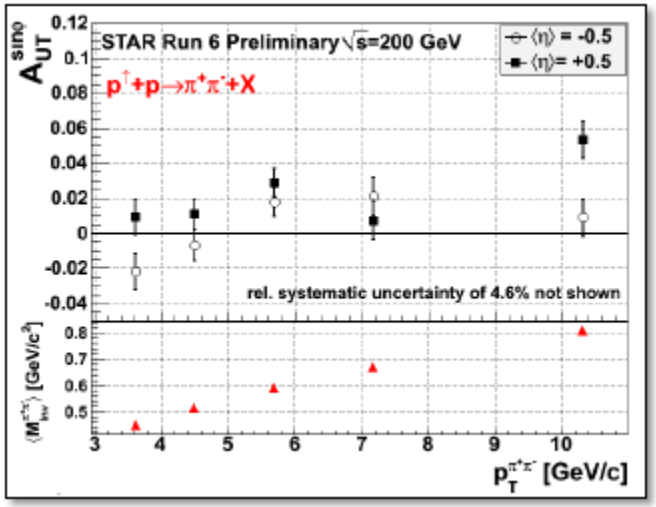
from scattering plane to hadron plane

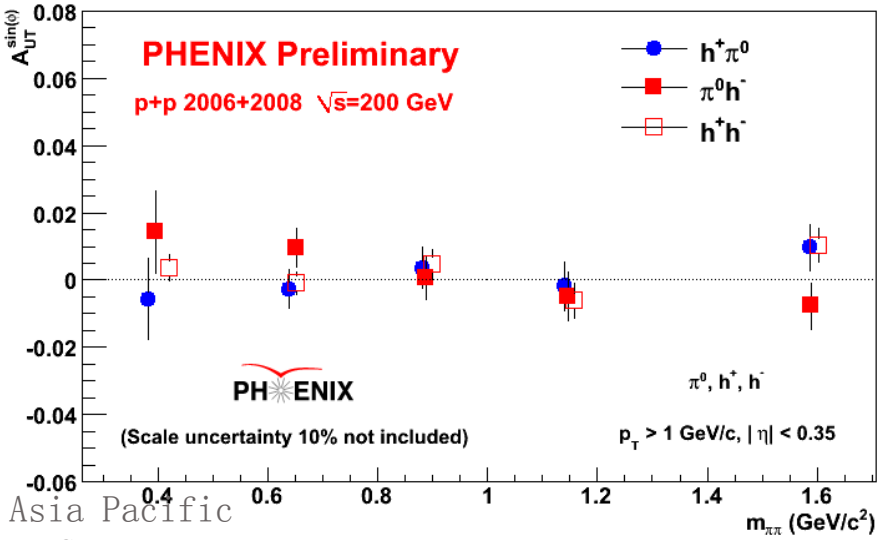
$$\cos\varphi_R = \frac{(P_C \times P_A)}{|P_C \times P_A|}\cdot\frac{(P_C \times R_C)}{|P_C \times R_C|}$$

IFF Measurement

- PHENIX measurement in 2006 and 2008 are consistent with zero
- STAR has seen non-zero?
- Analysis of 2012 data is on-going,
- Move to more forward





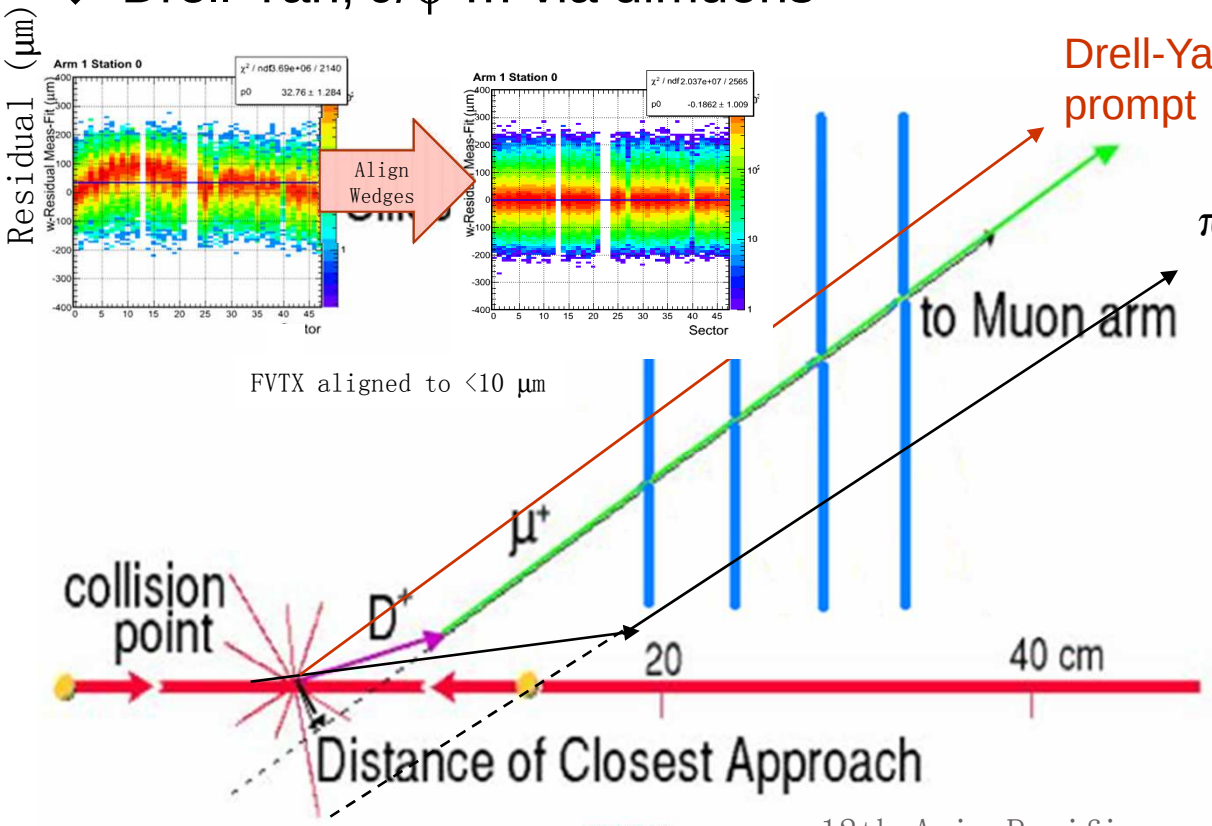


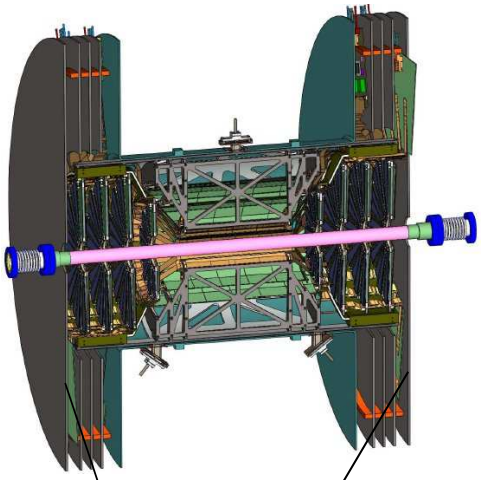
PHENIX Opportunities with New Detectors

FVTX installed in 2012

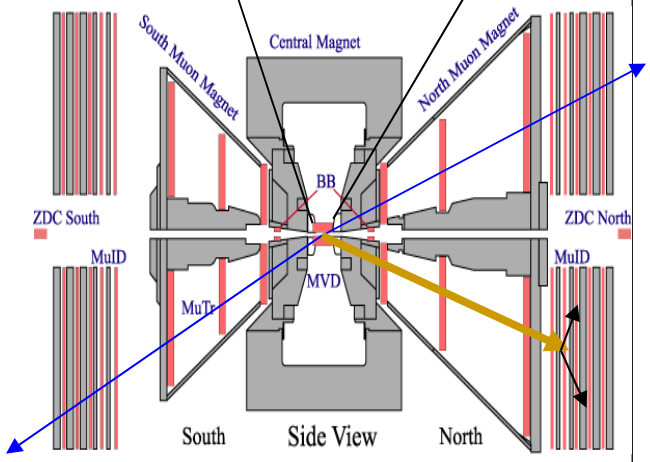
4 layers of FVTX end-caps cover
1.2<|η|<2.4 with resolution ~100um.

- Precise Charm/Beauty, W/Z Measurements
- Drell-Yan, J/ψ … via dimuons



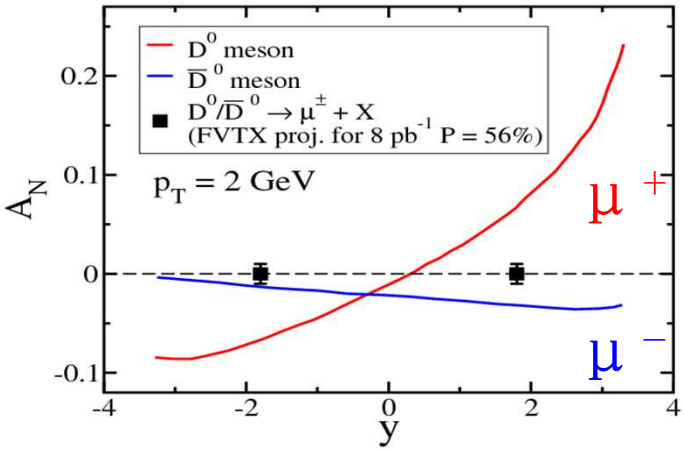


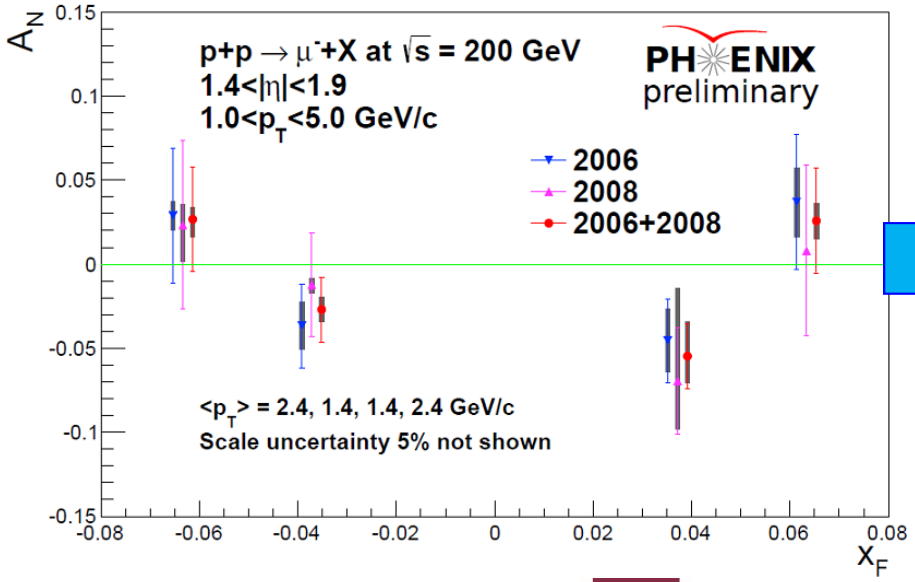
π→μ



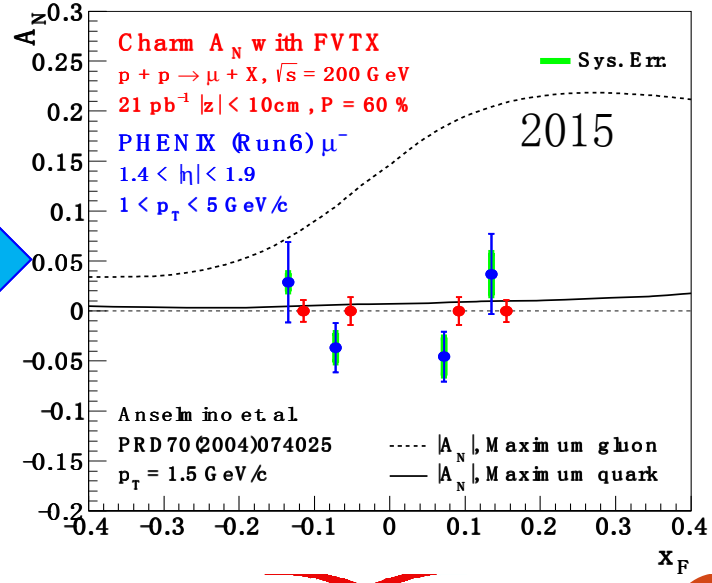
Projected Open Charm A_N with FVTX

- Significant rejection of hadron background
- Limited power on D/B separation
- Transverse spin data expected from 2015



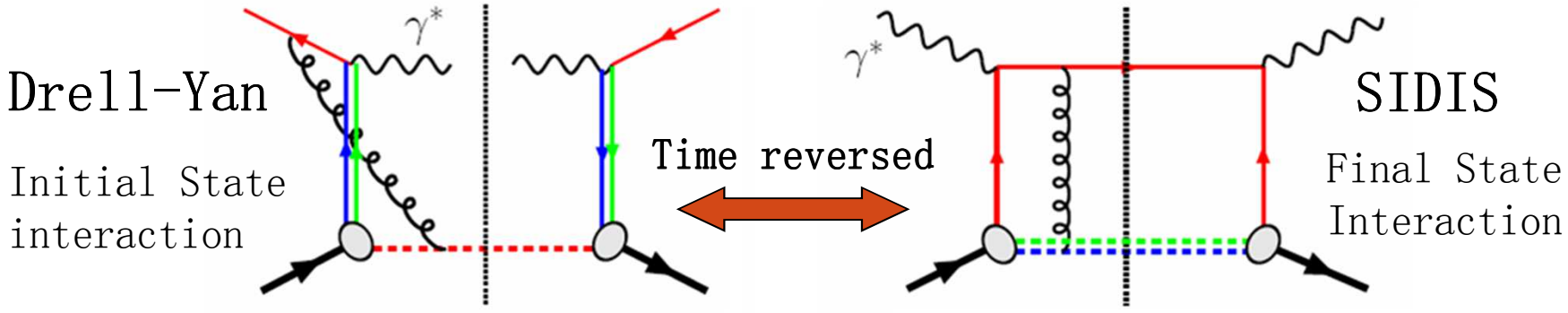


FVTX



Drell-Yan Process

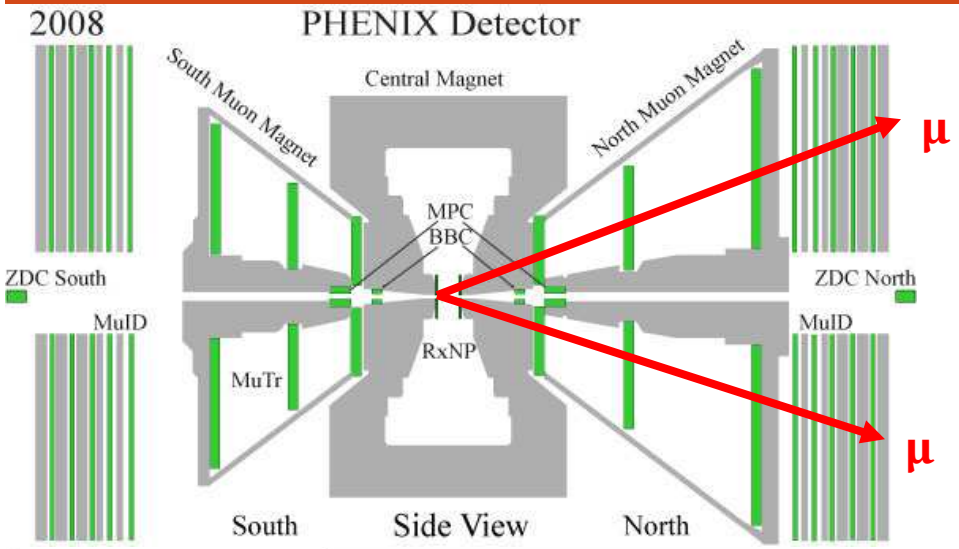
- No fragmentation (no Collins effect folded)
- TMD factorization is valid
- The Sivers function in DY is opposite to that in DIS which can test current SSA QCD mechanisms (TMD & Twist-3)
- A_{TT} in Drell-Yan is sensitive to transversity!

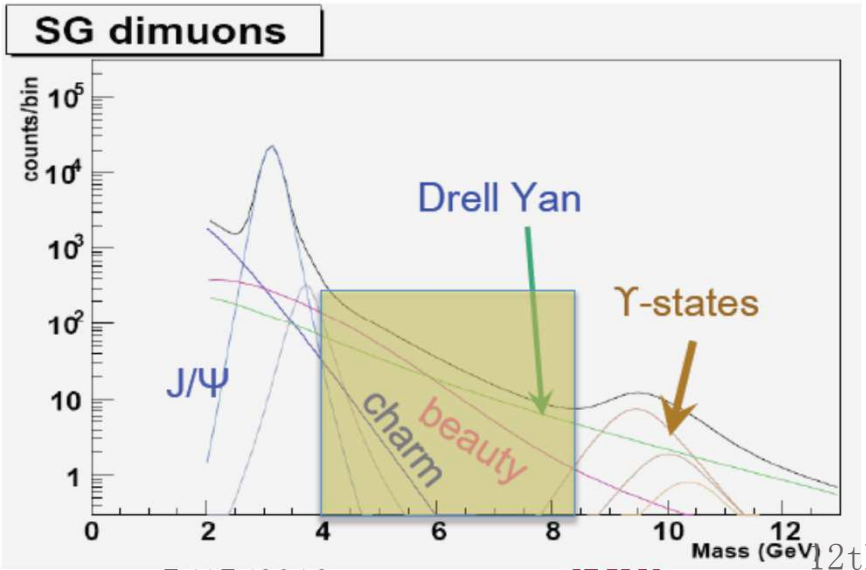


$$p + p \rightarrow l^+ + l^- + X \qquad l + p \rightarrow l + \pi + X$$

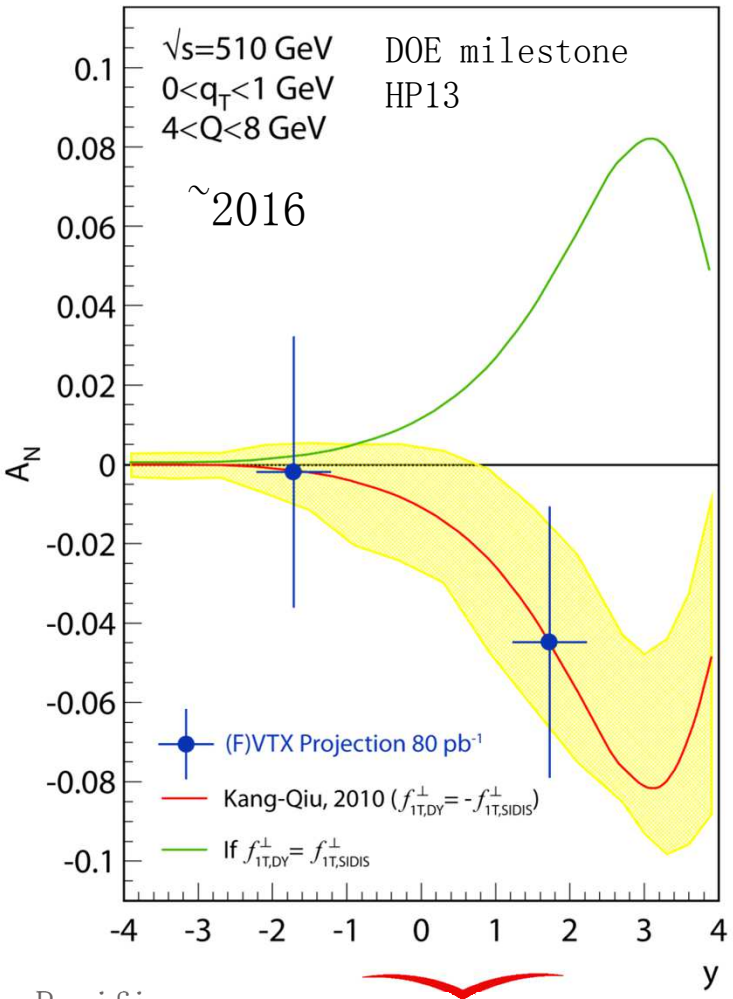
$$\Delta f_{1T}^{\perp}(x, \vec{k}_T^{\,2})\,|_{\text{Drell-Yan}} = -\Delta f_{1T}^{\perp}(x, \vec{k}_T^{\,2})\,|_{\text{SIDIS}}$$

Drell-Yan Projection

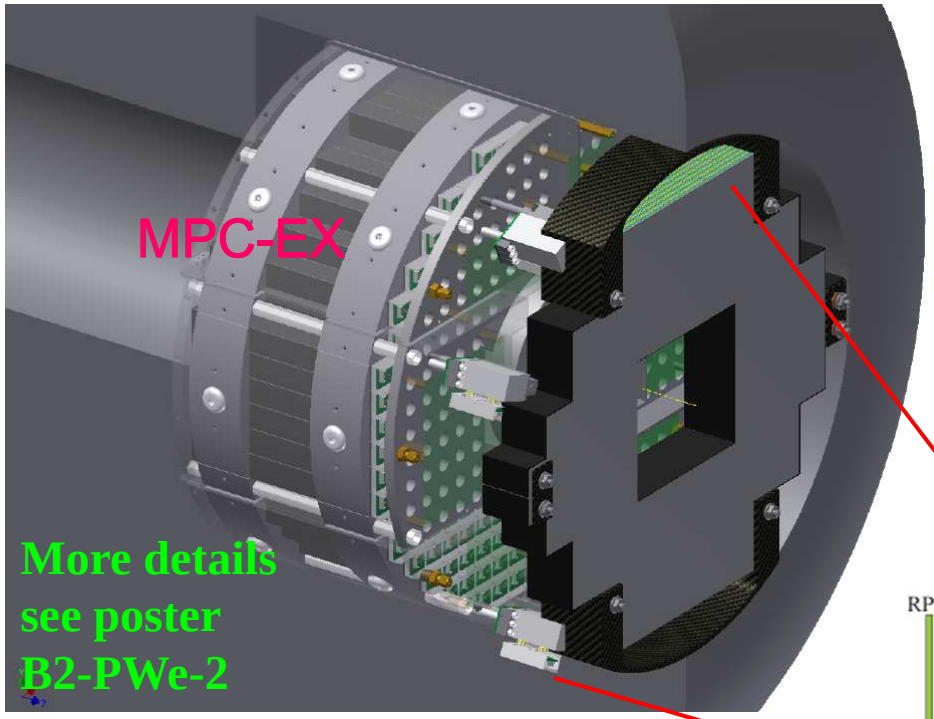


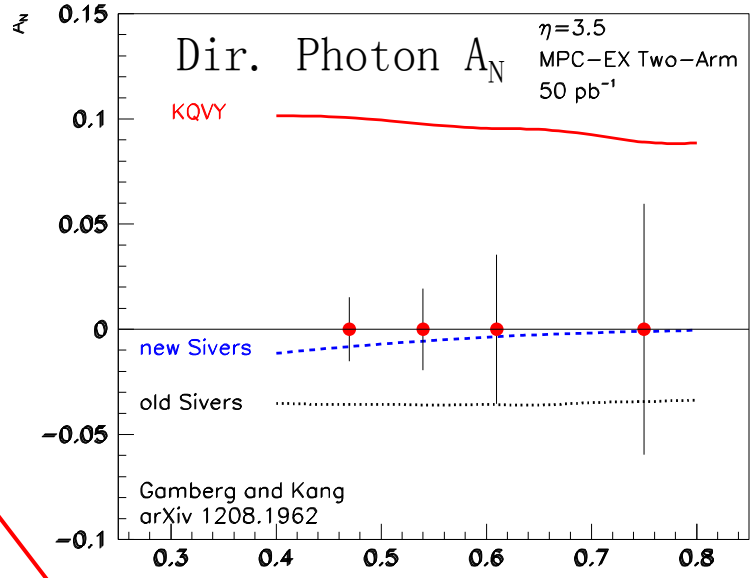


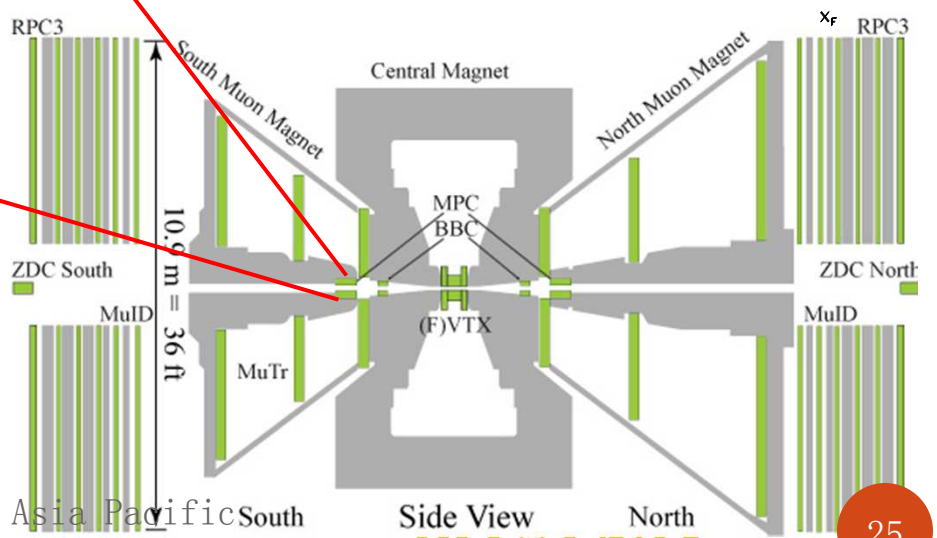
RHIC 1-year running projection



Coming soon: MPC-EX (2015+)







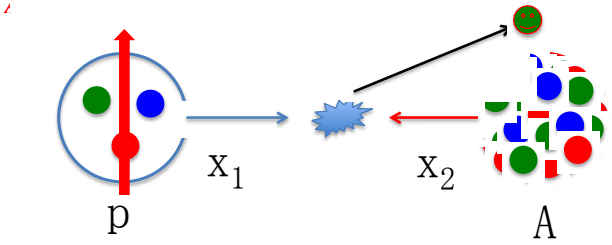
A combined charged particle tracker and EM pre-shower detector – dual gain readout allows sensitivity to MIPs and full energy EM showers.

$3.1<|\eta|<3.9$

- π^0 rejection → direct photons
- π^0 reconstruction out to >80GeV

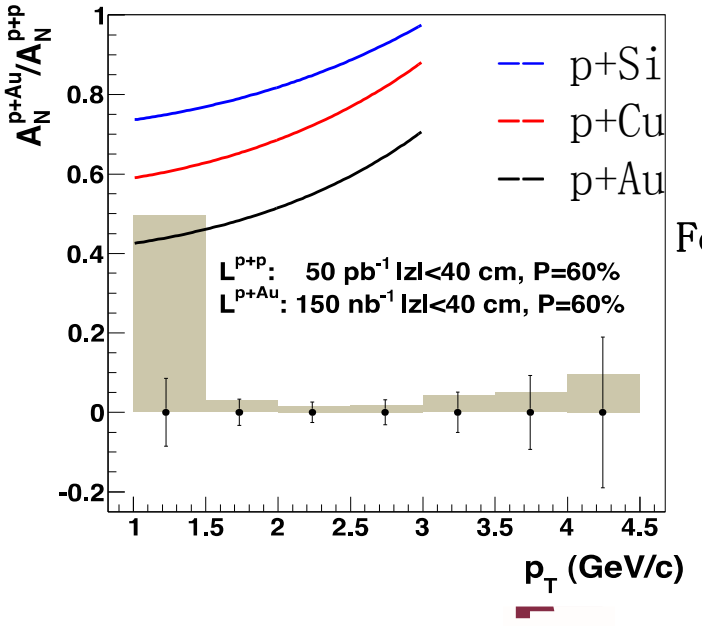
Polarized p+A at RHIC(2015+)

- Large transverse spin asymmetry A_N at forward rapidity – a large analyzing power at large x_1
- Gluon saturation/CGC probed at forward rapidity in p+A – small x_2 in A



projectile: $x_1 \sim \frac{p_\perp}{\sqrt{s}} e^{+y} \sim 1$ valence

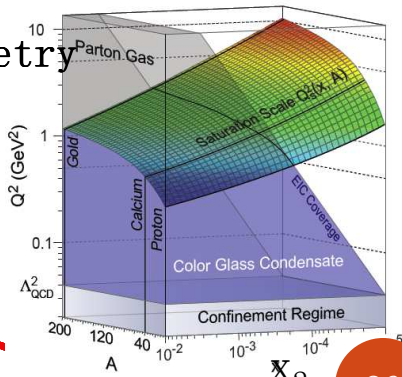
target: $x_2 \sim \frac{p_\perp}{\sqrt{s}} e^{-y} \ll 1$ gluon



$$\Delta\sigma_{forward} \sim \Delta f(x_1) \otimes g(x_2); \quad x_1 >> x_2$$

Forward Pion Single-Spin Asymmetry

$$\left. \frac{A_N^{pA \to h}}{A_N^{pp \to h}} \right|_{P_{h\perp}^2 \ll Q_s^2} \approx \frac{Q_{sp}^2}{Q_{sA}^2} e^{\frac{P_{h\perp}^2 \delta^2}{Q_{sp}^4}}$$



Kang, Yuan (2011)

Summary and Outlook

- **PHENIX has measured A_N in heavy flavor production**
  - Statistics is still limited and 2012 data will be included
  - Previous A_N of J/ψ was published and consistent with 2012 data
- **A_N of π^0 and η at mid- and forward rapidity was measured**
  - Current results prepare to be published
  - Expected much improved measurements with MPC-ex
- **A_N from Interference Fragmentation was measured**
  - Expect 2012 result soon with more forward measurement
- **Forward measurements with FVTX**
  - Expect significant background projection in heavy flavor production
  - Drell-Yan measurement becomes possible
- **More opportunities with polarized p+A experiments in future**

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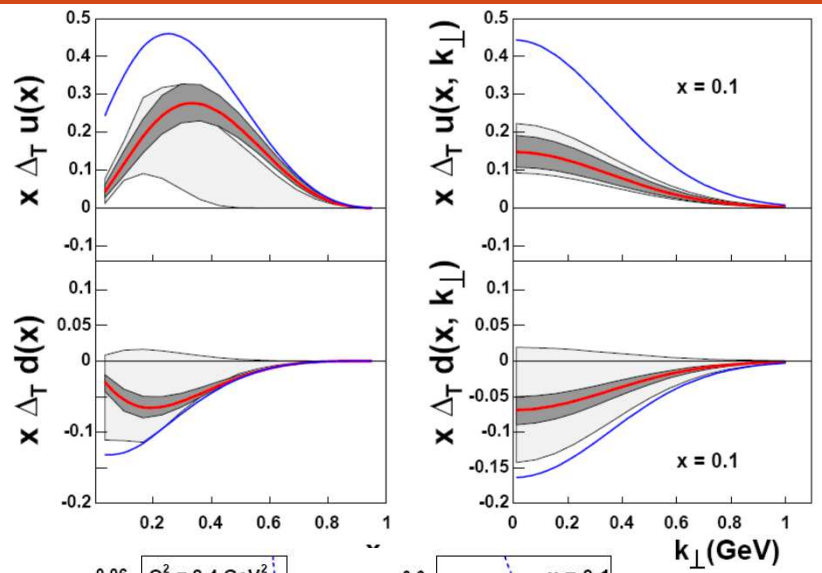
PHENIX 13 Countries; 70 Institutions

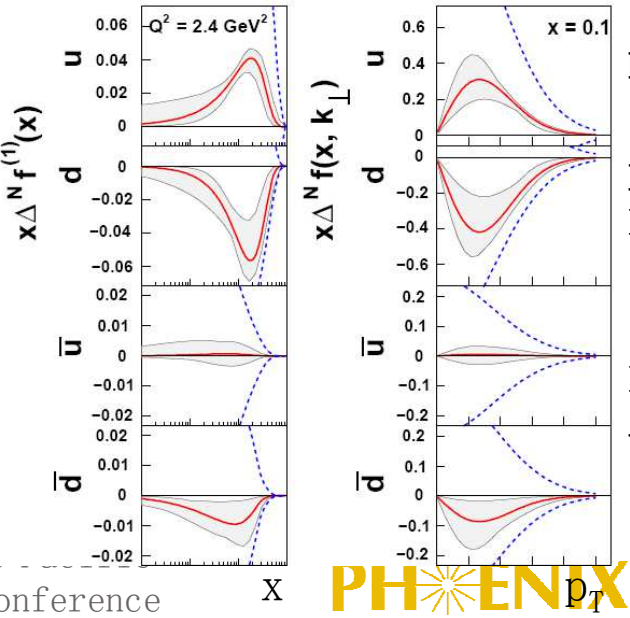
Thanks

Back up

Spin in transversely polarized proton

- Quark transversity
  - Know much better about quark transversity than before.
- Gluon transversity
  - No transversely polarized gluon.
- Parton orbital angular momentum
  - The Sivers function could be related to orbital angular momentum.
  - Quark Sivers function is constrained OK.
  - Gluon Sivers function is not well known.





M. Anselmino et. al.

Nucl. Phys. Proc. Suppl. 191, 98 (2009).

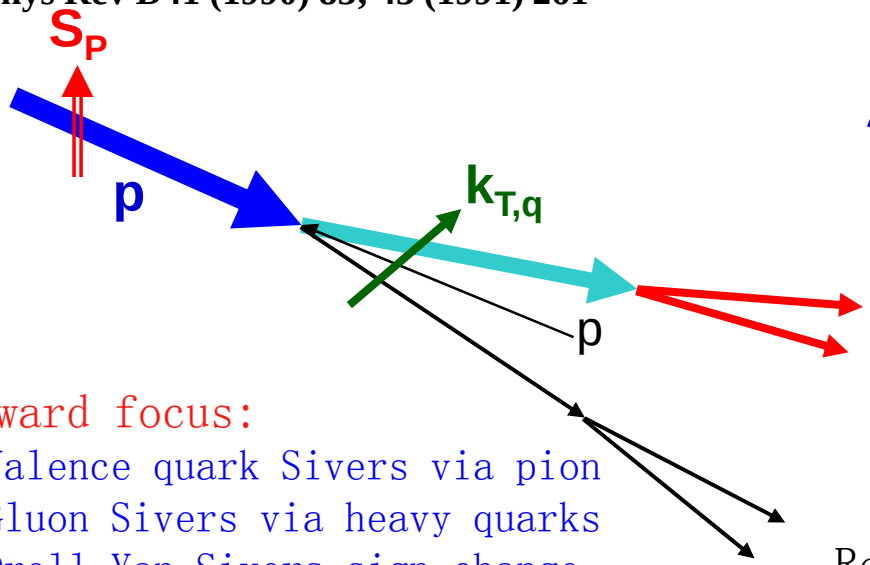
Eur. Phys. J. A39:89-100, 2009

Possible Mechanisms for A_N

- Quarks' Sivers and Collins TSSA observed in SIDIS
- Gluons' Sivers not constrained in SIDIS @LO

Sivers mechanism: Correlation between nucleon spin and parton k_T

Phys Rev D41 (1990) 83; 43 (1991) 261

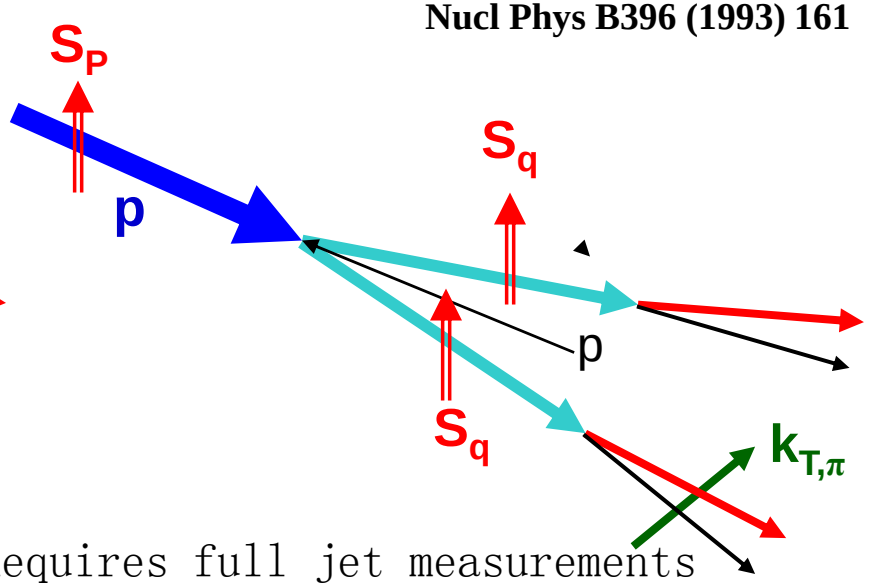


Forward focus:
- Valence quark Sivers via pion
- Gluon Sivers via heavy quarks
- Drell-Yan Sivers sign change

Orbital Angular Momentum?

Collins mechanism: Transversity (quark polarization) * Spin-dependence in the jet fragmentation

Nucl Phys B396 (1993) 161

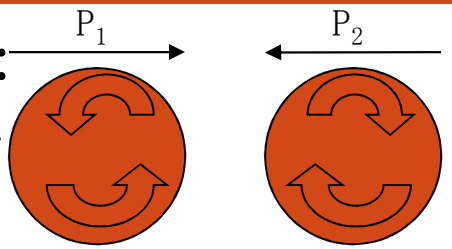


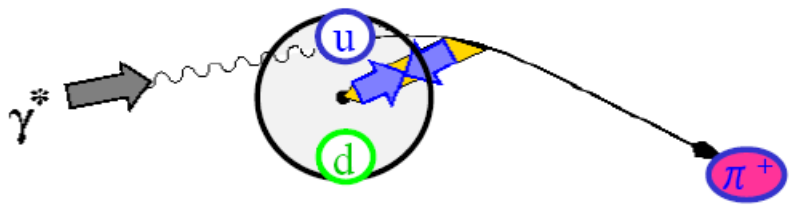
Requires full jet measurements
- forward s/ePHENIX upgrade

Semi-classical Interpretation

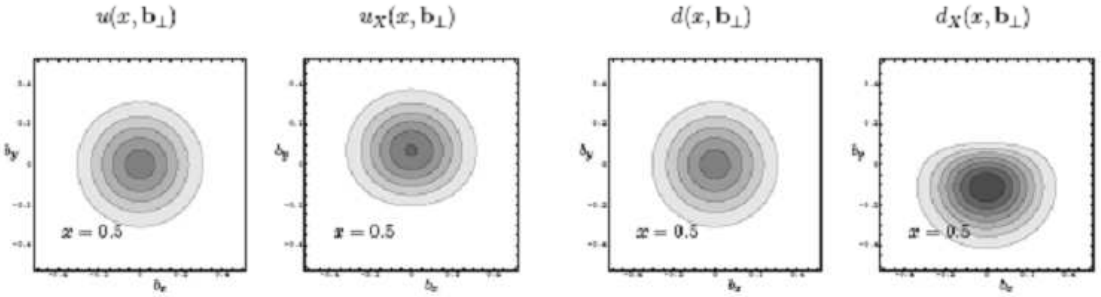
Two Possibilities:

1. Nuclear Shadowing (angular momentum)

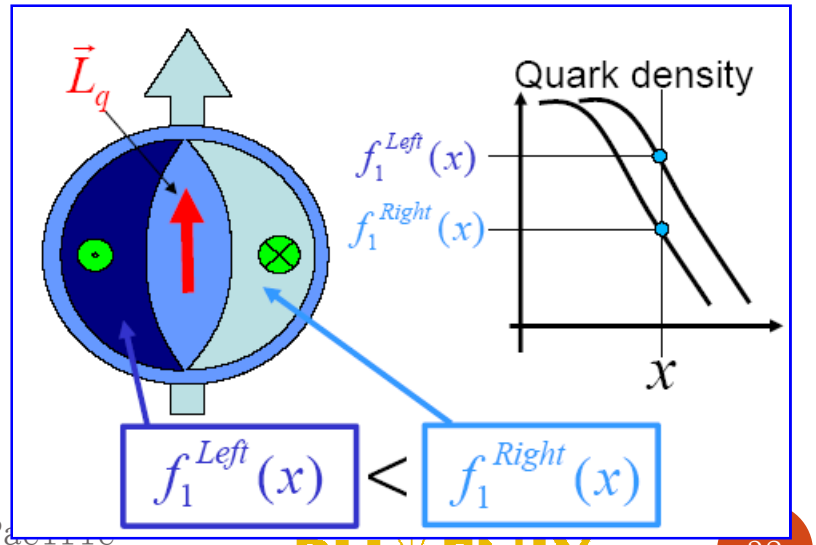




2. Impact Parameter Space Changes with polarization



- Attractive rescattering of hit quark by gluon creates transverse momentum
- M.Burkardt [hep-ph0309269] – impact parameter formalism
- Orbital angular momentum at finite impact parameter
- Observed and true x differ
- Observable left/right asymmetry



Heavy Quark TSSA at RHIC

Twist-3 tri-gluon correlation functions

$$P_h^0 \frac{d\sigma^{3\text{gluon}}}{d^3P_h} \simeq \frac{\alpha_s^2 M_N \pi}{S} \epsilon^{P_h p n S_\perp} \sum_{f=c\bar{c}} \int \frac{dx'}{x'} G(x') \int \frac{dz}{z^3} D_a(z) \int \frac{dx}{x} \delta\left(\tilde{s}+\tilde{t}+\tilde{u}\right) \frac{1}{\tilde{u}}$$
$$\times \left[\delta_f \left(\frac{d}{dx} O(x) - \frac{2O(x)}{x}\right) \hat{\sigma}^{O1} + \left(\frac{d}{dx} N(x) - \frac{2N(x)}{x}\right) \hat{\sigma}^{N1}\right].$$

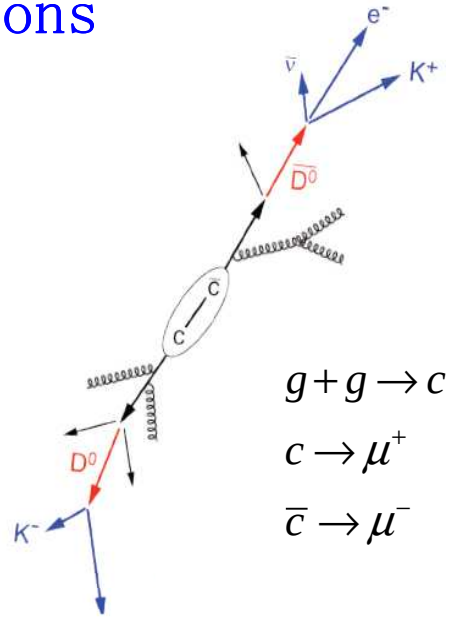
where $O(x) \equiv O(x,x) + O(x,0)$, $N(x) \equiv N(x,x) - N(x,0)$.

$\delta_f = +1(c);\ -1(\bar{c})$

$$A_N(D) \overset{?}{\neq} A_N(\bar{D})$$

Model 1:
$O(x) = 0.004 x G(x)$

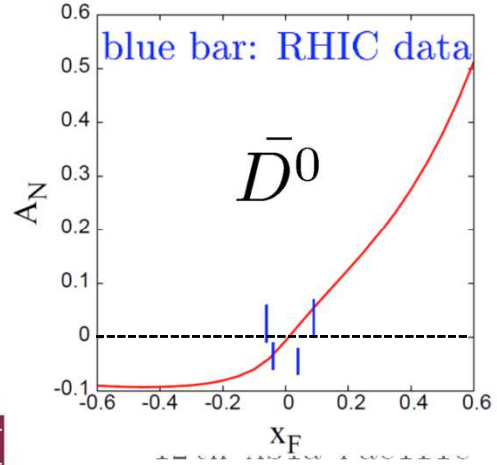
Koike *et. al.* (2011)
Kang, Qiu, Vogelsang, Yuan (2008)

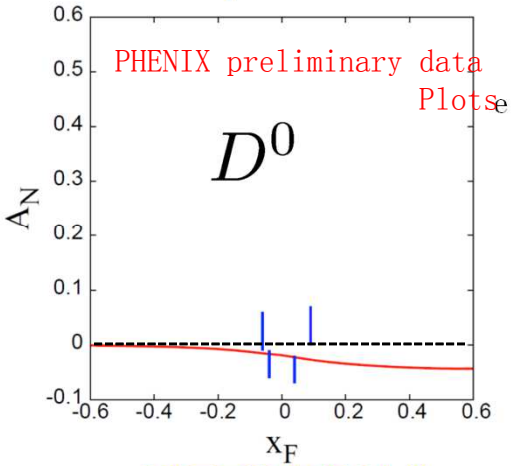


$g + g \to c + \bar{c}$

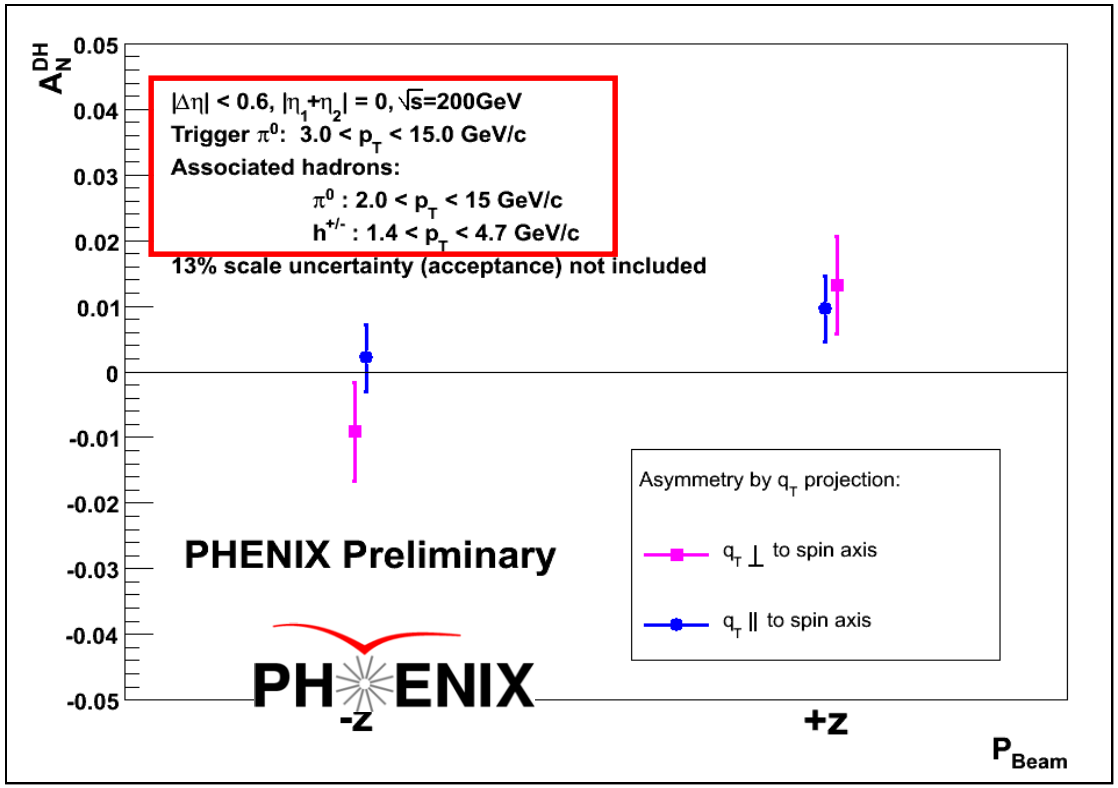
$c \to \mu^+$

$\bar{c} \to \mu^-$





A_N for Di-hadron



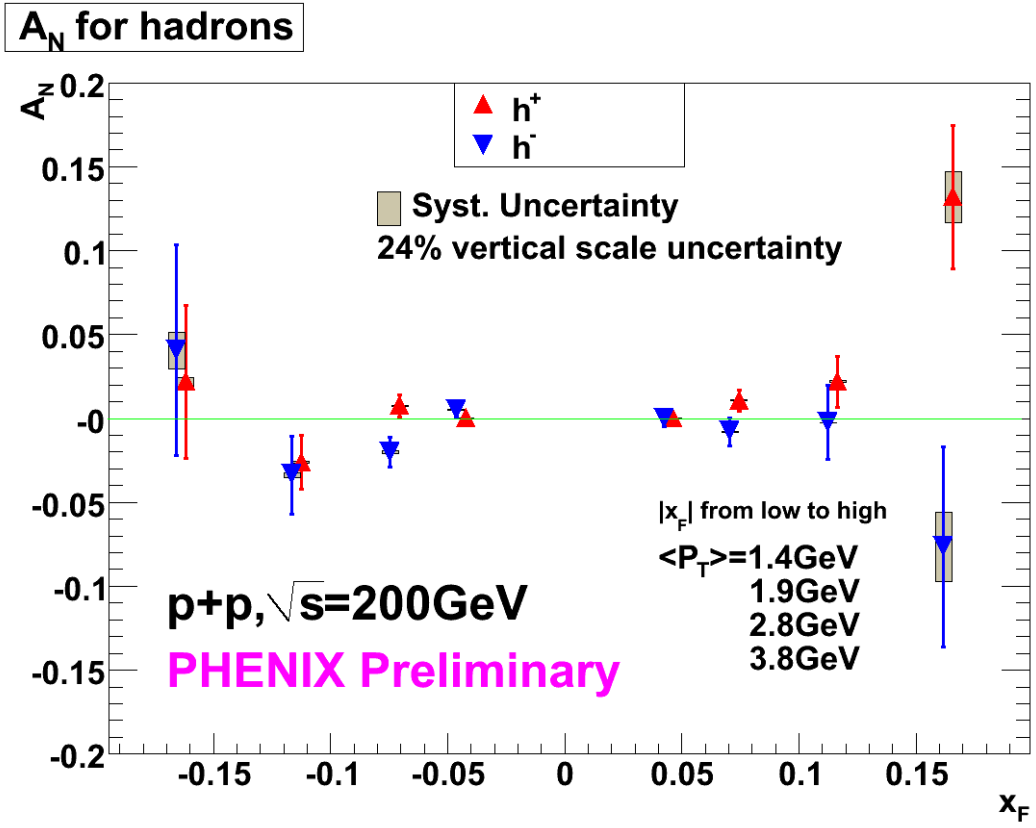
- Sivers asymmetry ($q_T\perp$)
- No asymmetry expected for $q_T\parallel$
- Improved statistics for 2008 data set!

TMD is not valid for back to back di-hadron process in p+p collision

Similar analysis possible in different combinations of rapidity

η_{min}	-3.7	-2.4	-0.35	1.2	3.1
η_{max}	-3.1	-1.2	+0.35	2.4	3.9

Forward A_N for Charged Hadrons



- Measured at Muon Arms $1.2<|\eta|<2.4$
- No PID - Unidentified charge hadrons